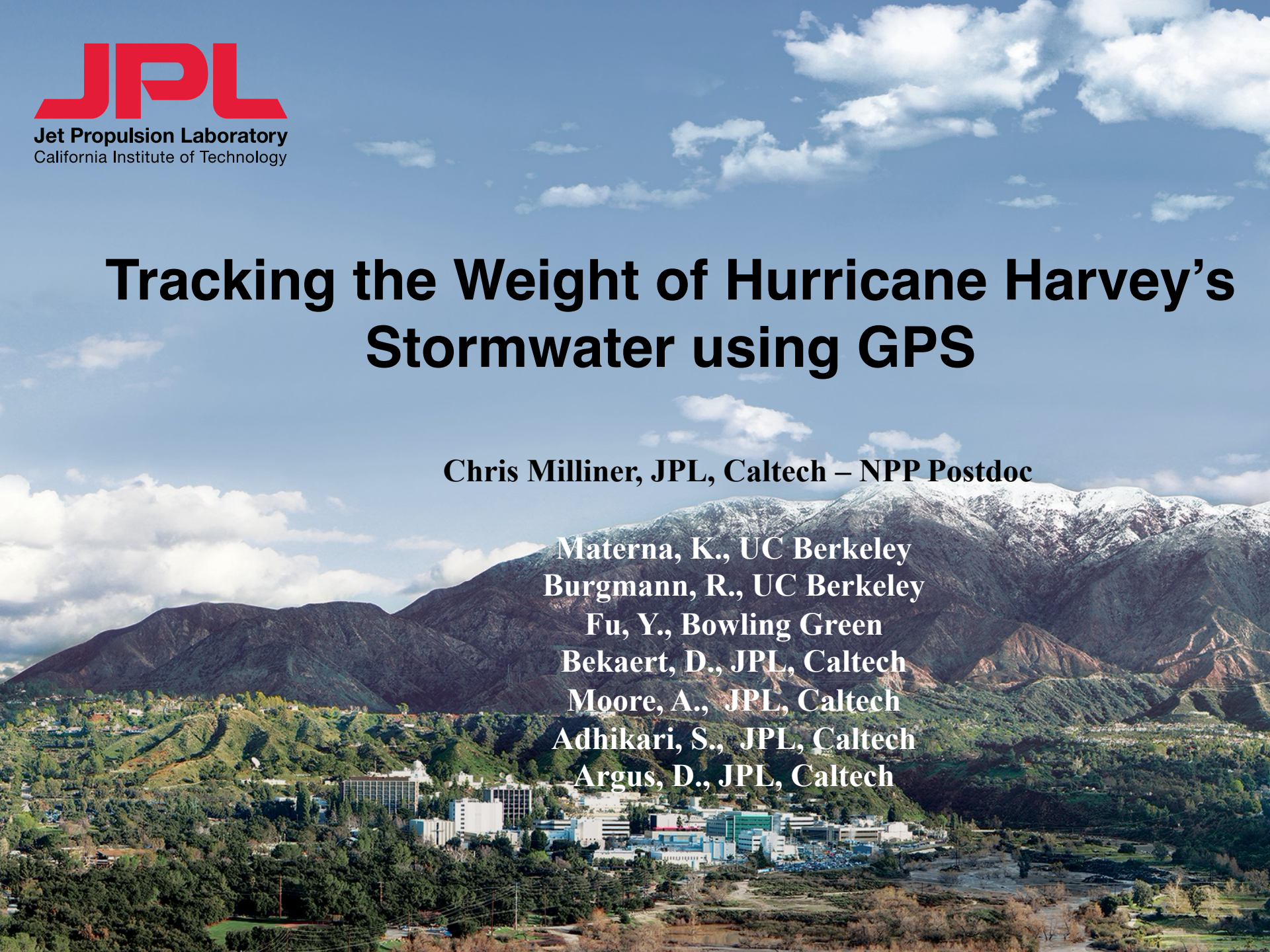


Jet Propulsion Laboratory
California Institute of Technology

Tracking the Weight of Hurricane Harvey's Stormwater using GPS

Chris Milliner, JPL, Caltech – NPP Postdoc

Materna, K., UC Berkeley
Burgmann, R., UC Berkeley
Fu, Y., Bowling Green
Bekaert, D., JPL, Caltech
Moore, A., JPL, Caltech
Adhikari, S., JPL, Caltech
Argus, D., JPL, Caltech

Introduction

- **Question**: How does stormwater accumulate and dissipate on land following a major hurricane?
  - What happens to stormwater once deposited?

- **Method:** Use GPS positioning to measure solid Earth's elastic surface response to water mass → this can be used to track the daily evolution of TWS
  - TWS = standing surface water, absorbed into soil + ground water.

- **Motivation:** Quantifying TWS important for:
  - **Understanding**: important component of hydrologic system, difficult to measure.
  - **Applications**: constraining hydrologic simulations → operational flood forecasts

Background

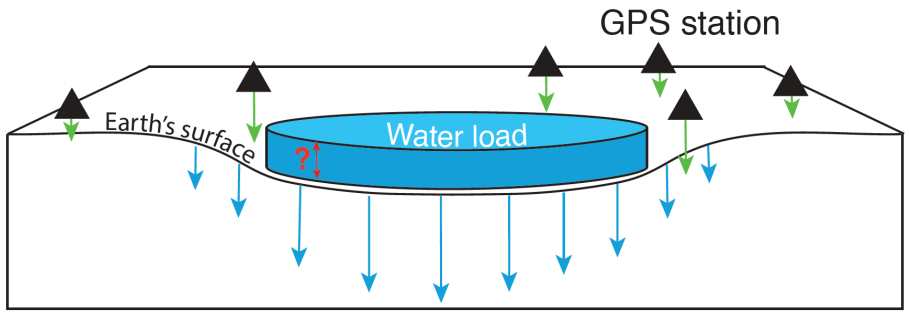
NOAA - Stage IV

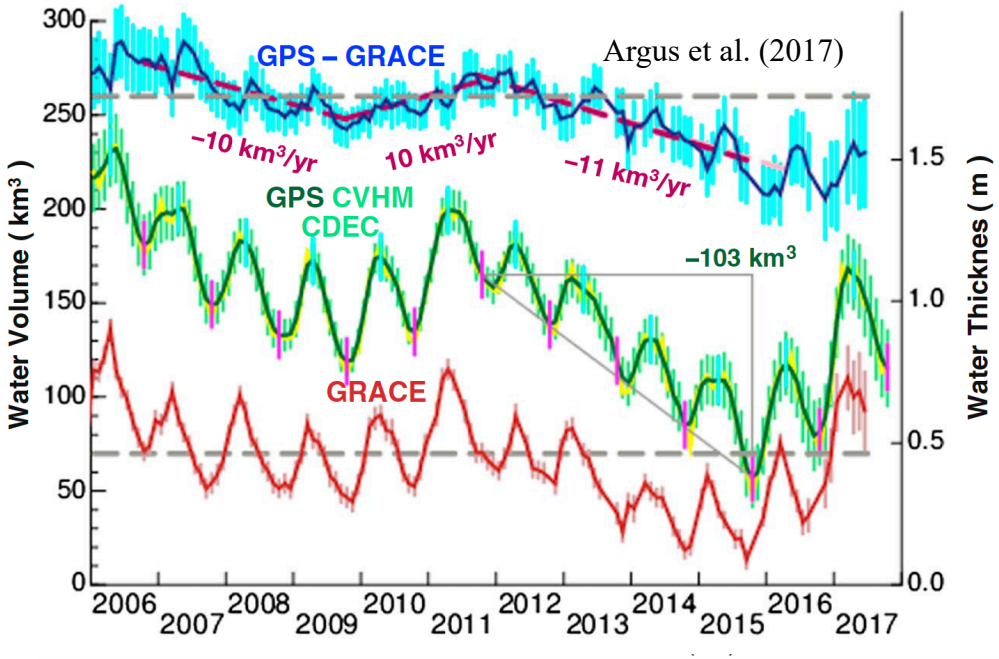
Elastic Earth

- Main idea: Water loads Earth's elastic crust → surface deformation.

- **Challenge**: Resolving hydrologic loading from noisy (WRMS 6 mm) GPS timeseries.
  - Long timescales (months-seasons) to characterize loading.

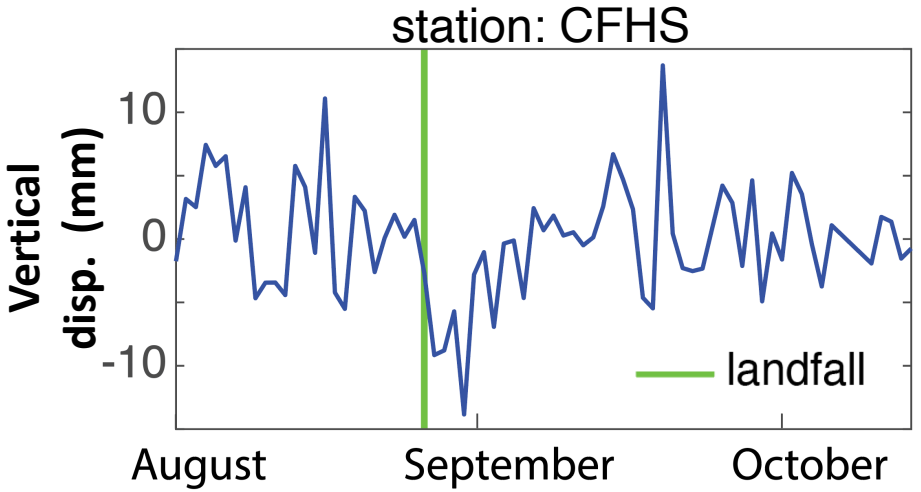
- Is GPS positioning precision sufficient to resolve Harvey's transient loading signature?





GPS Data

- Total of 219 GPS stations
  - East, north and vertical
- Data processed using JPL's GIPSY-OASIS II, in PPP.
- Average spacing ~30 km
- Correct for:
  - tidal ocean loading
  - solid Earth body tides
  - non-tidal ocean & atmospheric pressure changes

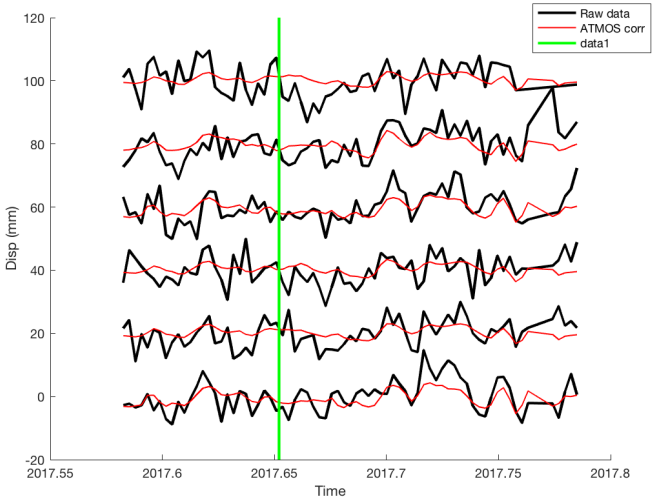


Non-tidal atmosphere + ocean loading (IERS/GFZ)

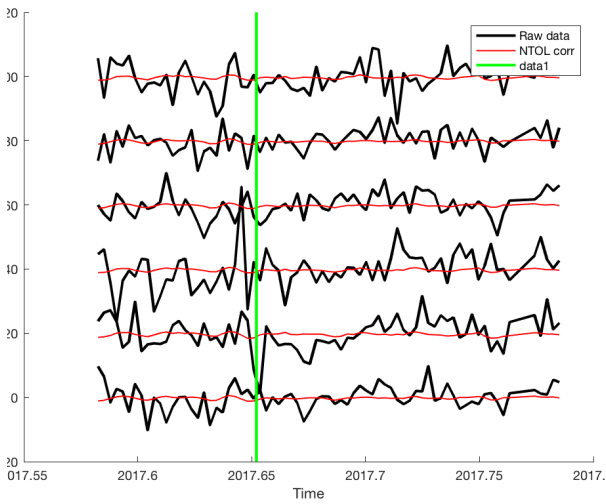
Black = data
Red = correction
Green = landfall of Harvey

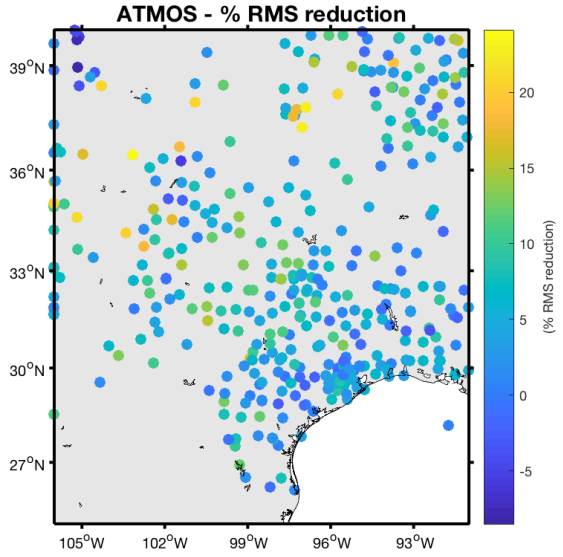
- Corrections for non-tidal atmospheric loading + ocean loading
- Effect of atmospheric pressure changes unloading-loading surface.
- ATMOS: RMS average reduction =up to ~20%
- NTOL RMS reduction up to 10% near-shore

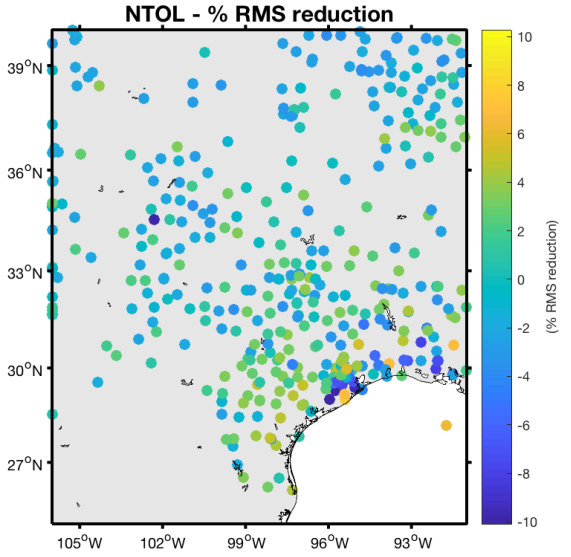
Atmospheric loading (red)



NTOL correction (red)



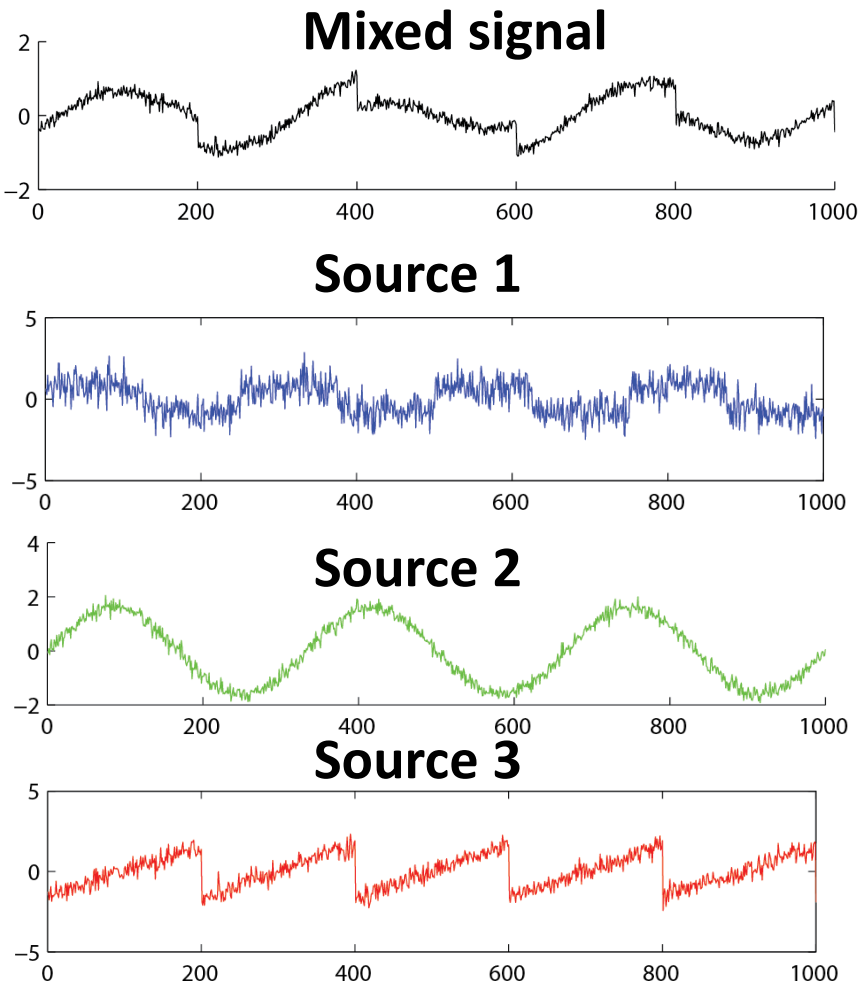


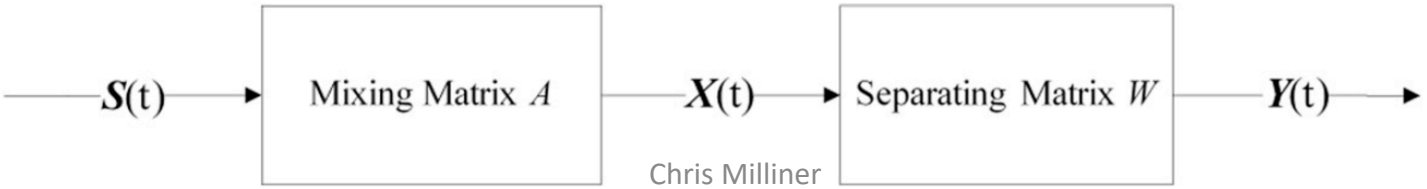


ICA - Independent Component Analysis

- GPS vertical is noisiest component → ICA to extract hydro signal
- ICA – identifies and un-mixes sources across the GPS network of maximum independence (Hyvärinen & Oja, 2000).

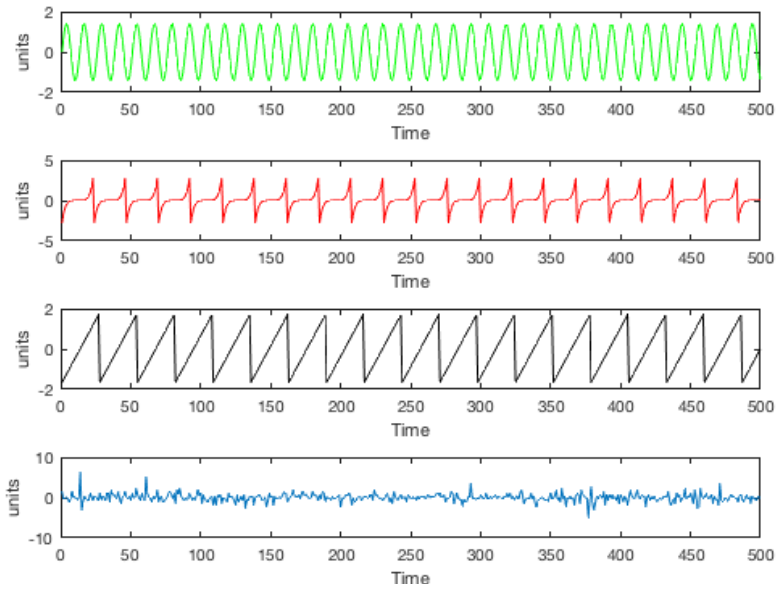
- Data timeseries = linear combination of time-varying independent components with spatial weight
- **CME** = network wide motions due to inaccuracies in:
  - satellite orbits
  - Tropospheric/ atmospheric models.





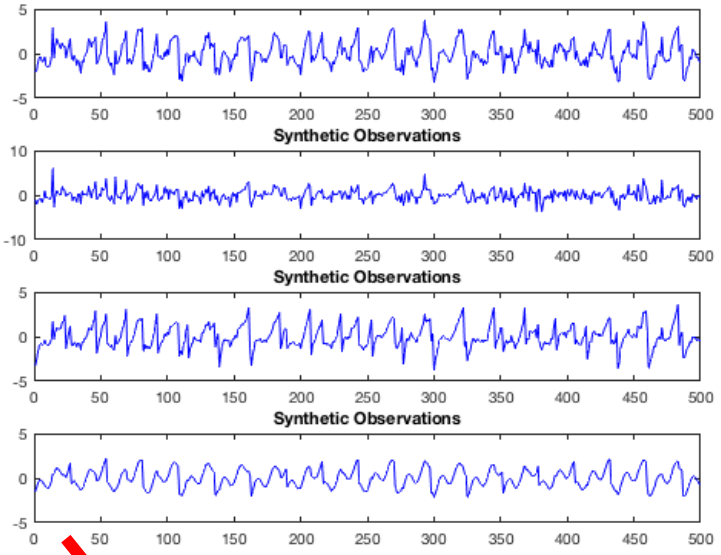
Synthetic tests – ICA vs PCA

Synthetic sources

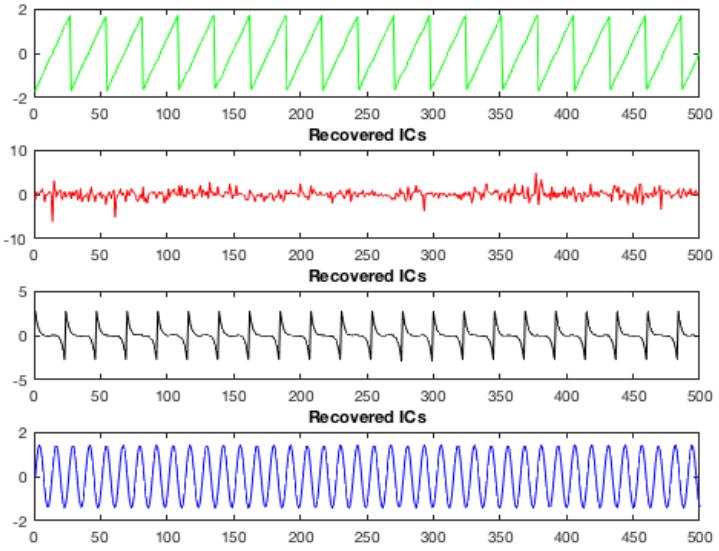


Randomly mix

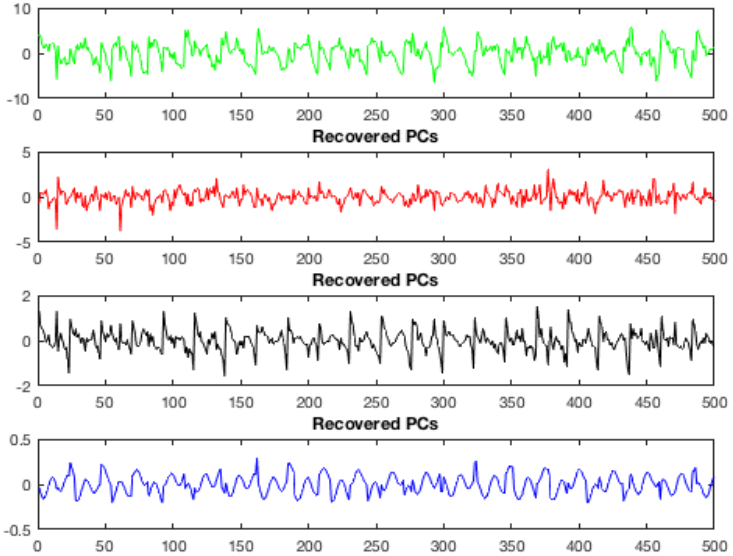
Synthetic Observations



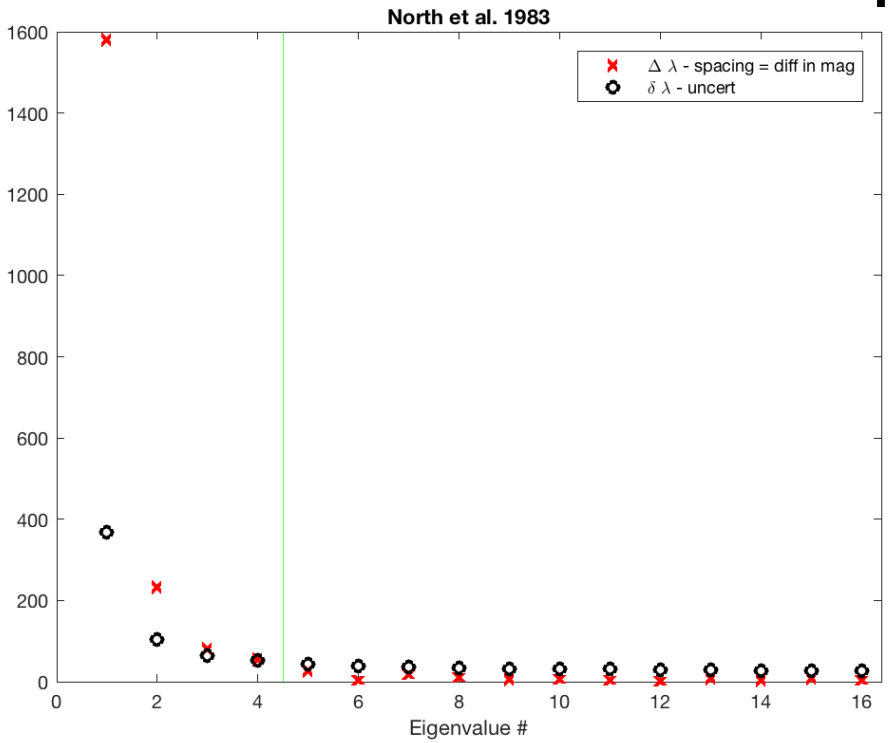
ICA recovered sources

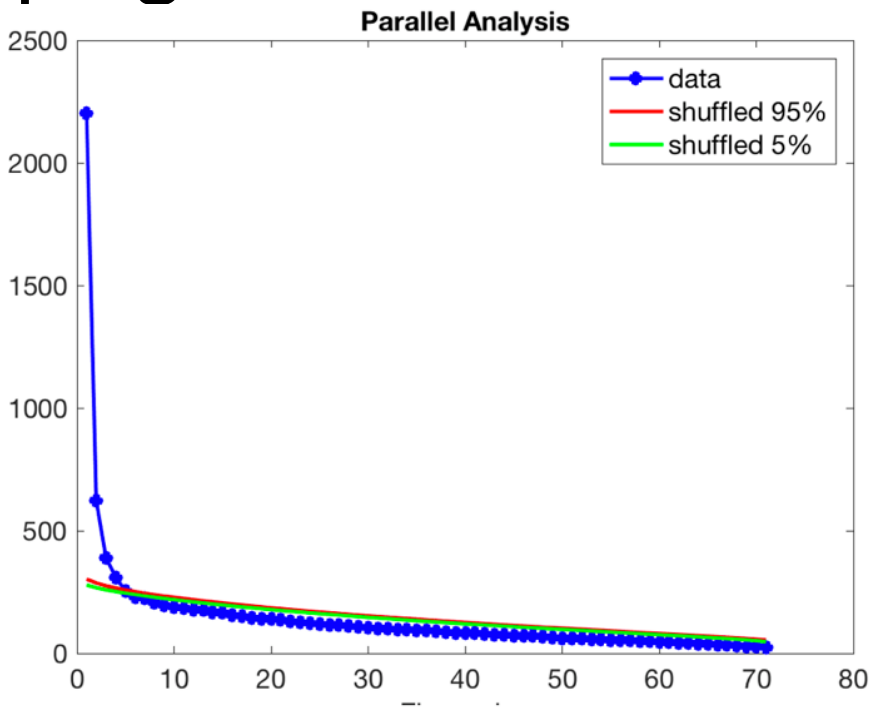


PCA recovered sources



How many components to decompose data? - Stopping rules





"North's rule of thumb": Measure of seperability

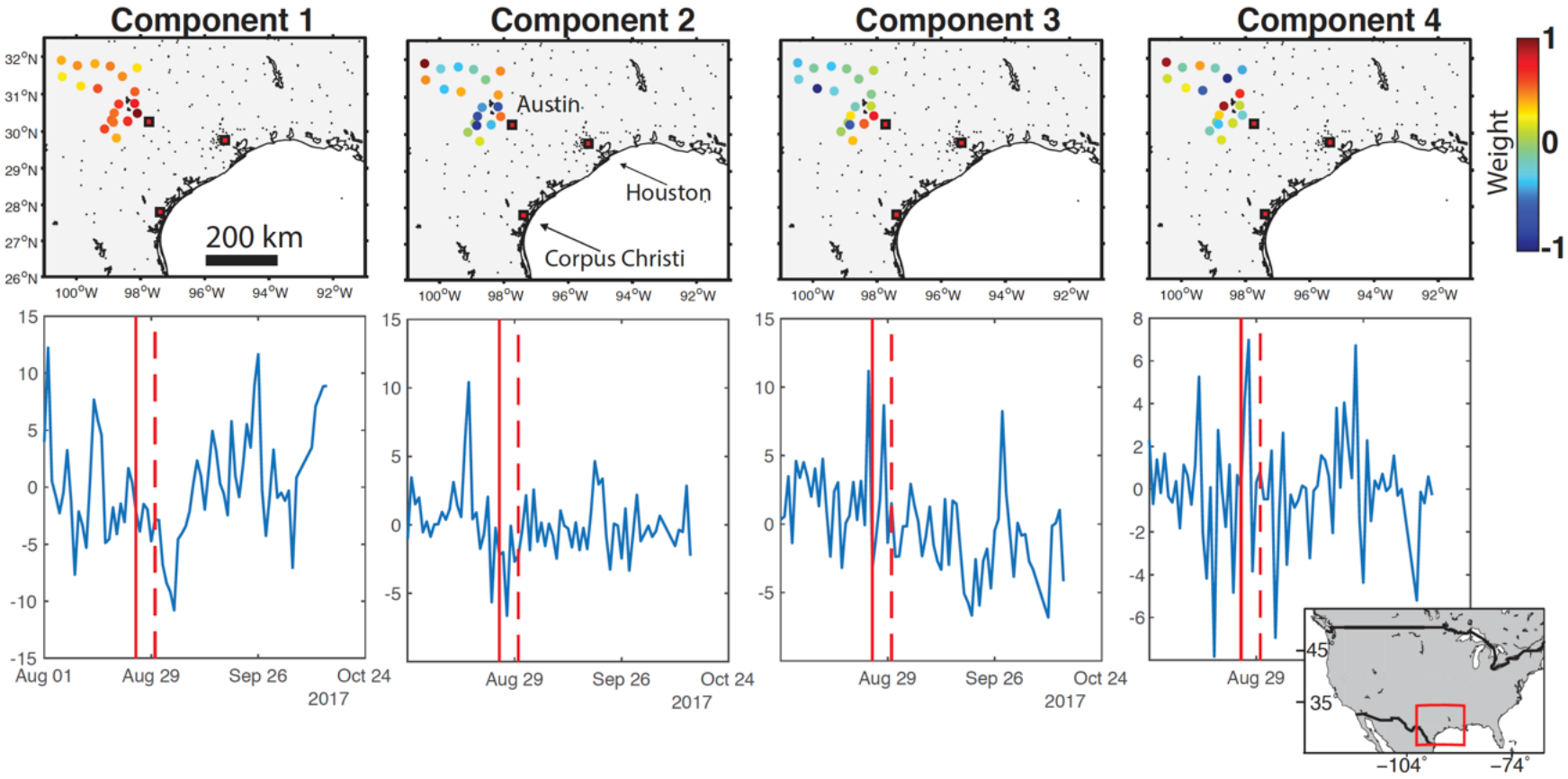
Idea: Assess which eigenvalues exceed that expected from a random process:

1. If uncert. exceeds separation, then component is deemed difficult to separate from its neighbor and from noise.

Horn's Parallel Analysis

- Randomly scramble the data → suite of random samples and eigenspectra with 95% CI.
- If eigenvalue > 95% of eigenvalues from random data then component is retained.

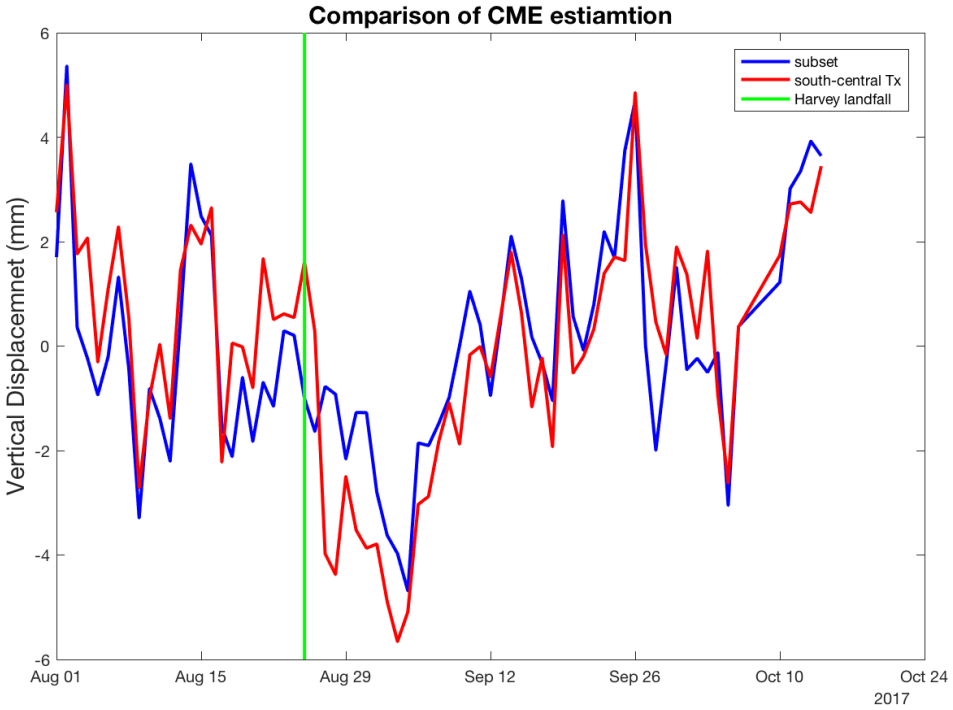
ICA filtering

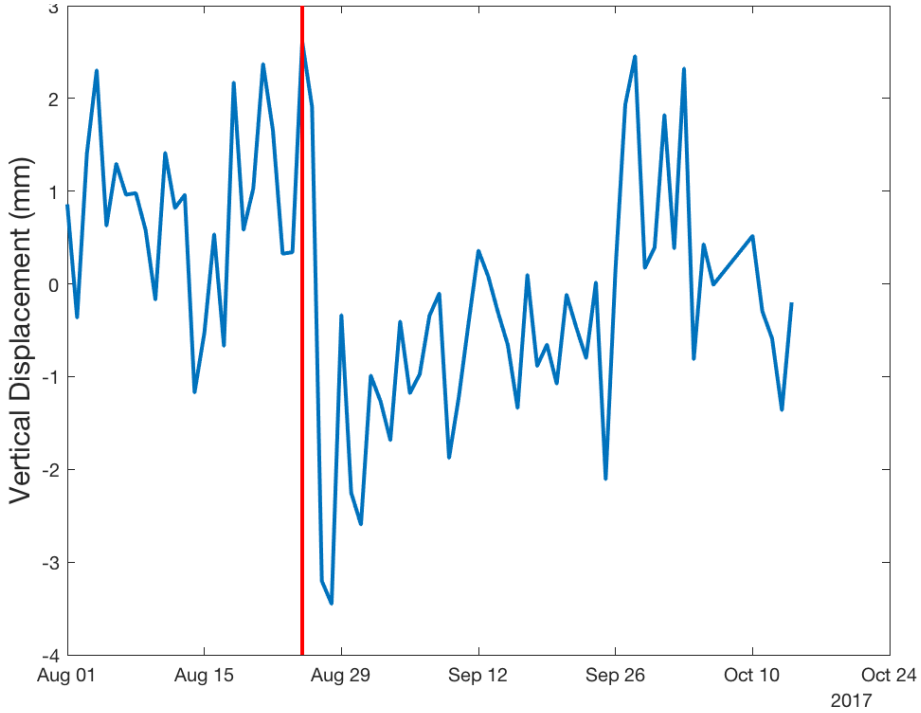


- Components ordered in amount of motion explained.
- CME shows ~10 mm of subsidence, second landfall not detected.
- Hydrologic signal mixed onto first component

- Instead we estimate ‘CME’ from a subset of stations, distal from known precipitation
- Assume this CME is uniform across network

Comparing CME estimates





Red = CME from entire network

Blue = CME from subset of stations

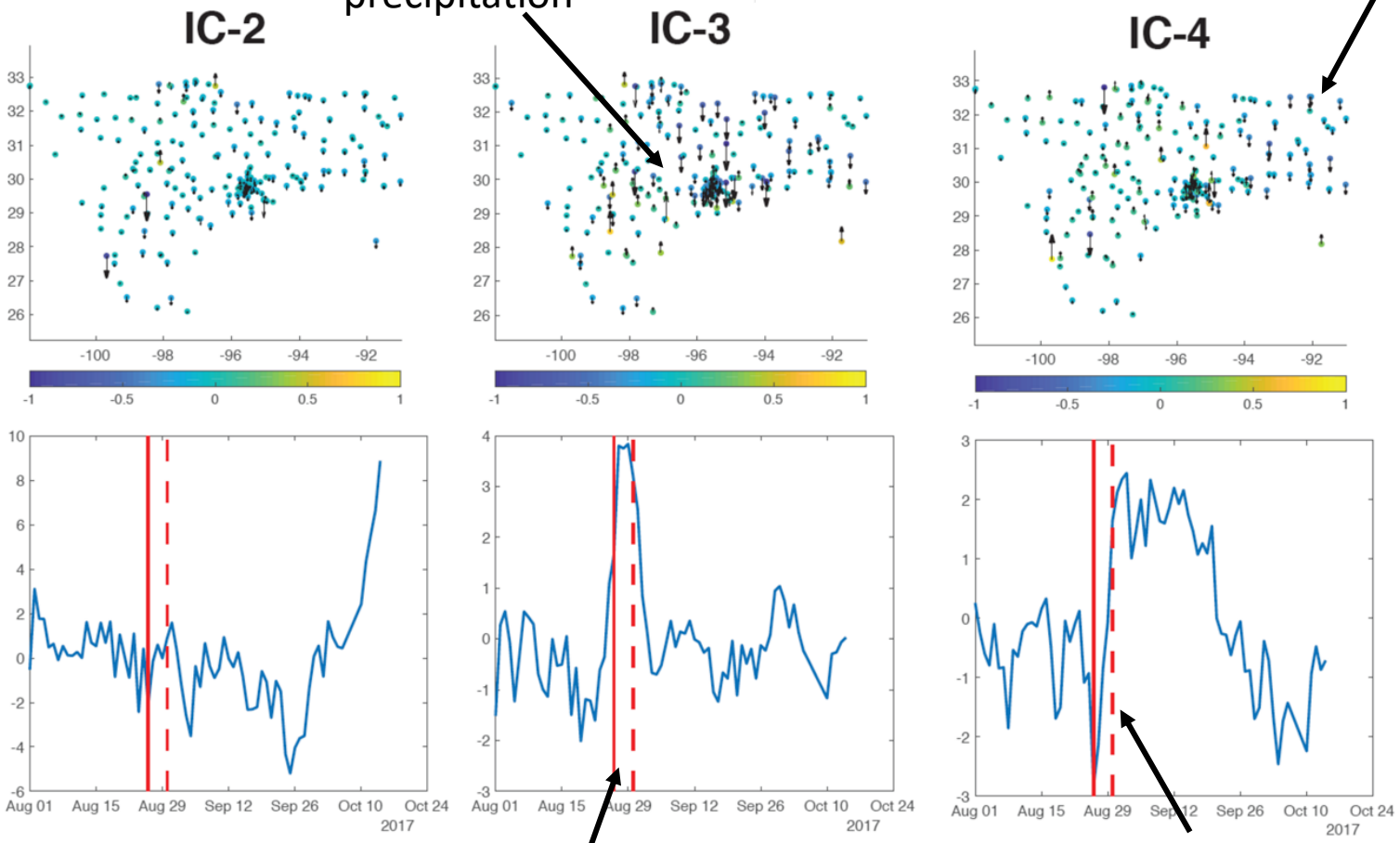
Green = Landfall

- Above: Difference between two CME estimates
- Marked subsidence coincident with Harvey landfall (red line)
- Followed by gradual uplift
- Suggests hydrologic signal is mixed with CME

East component (after CME removed)

Hydrologic signal:
Area of known precipitation

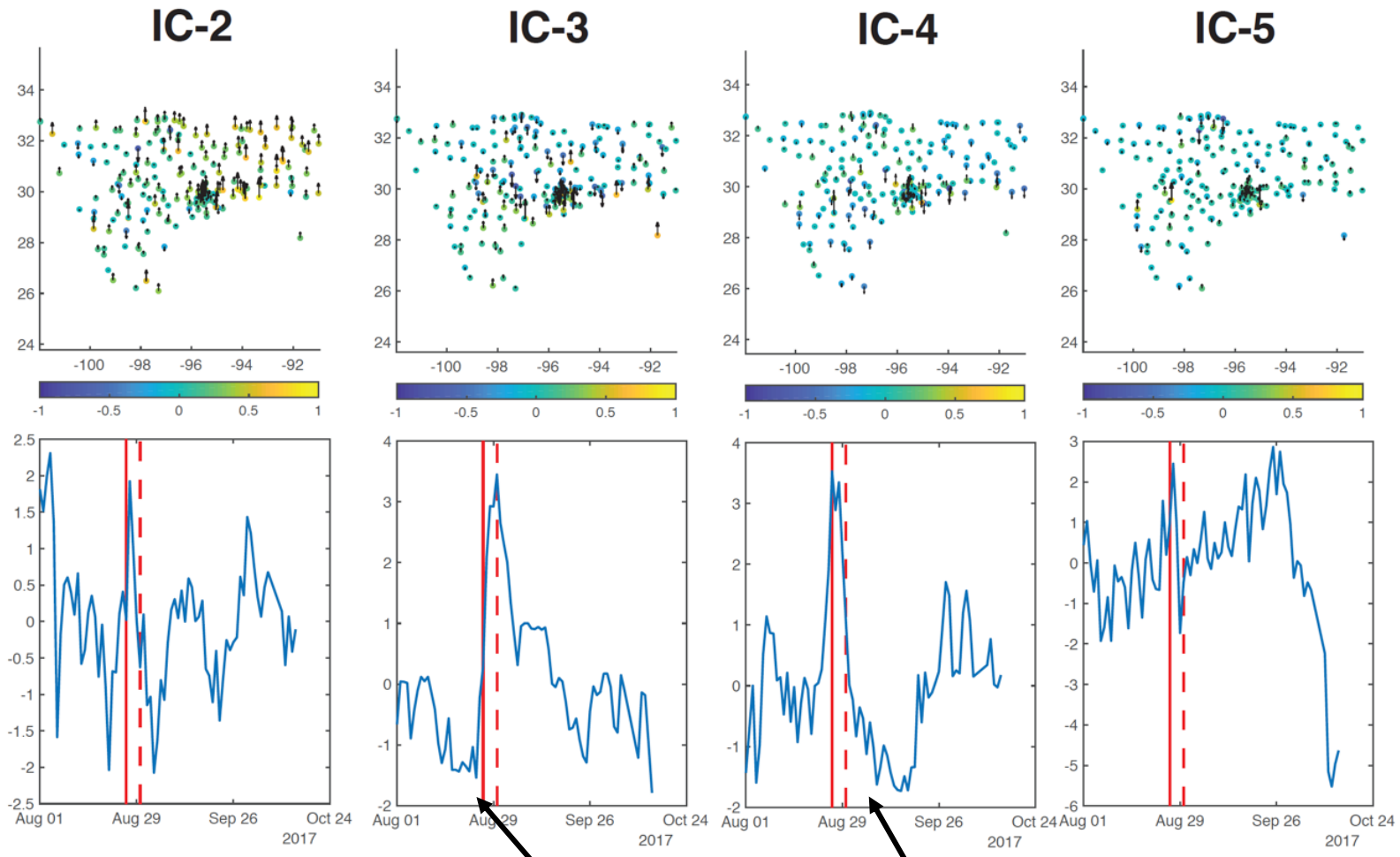
Hydrologic signal:
Area of second landfall



Hydrologic signal:
Coincident with initial landfall

Hydrologic signal:
Coincident with second landfall

North component (after CME removed)

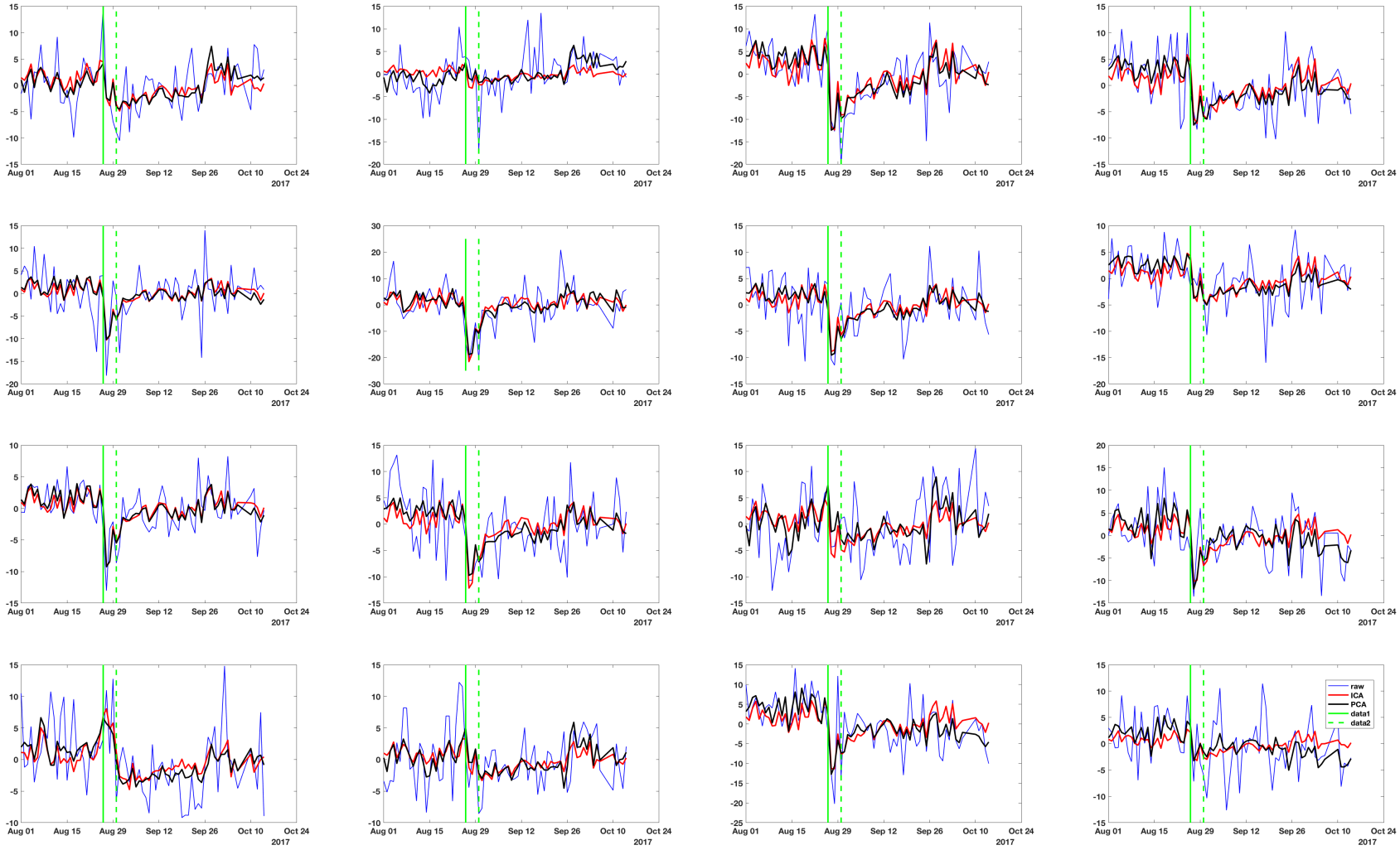


Other components not kept, show temporally inchorenet motion or spatial patterns not consistent with Harveys landfall pattern

Hydrologic signal: Coincident with initial landfall

Hydrologic signal: Coincident with second landfall

Filtered data

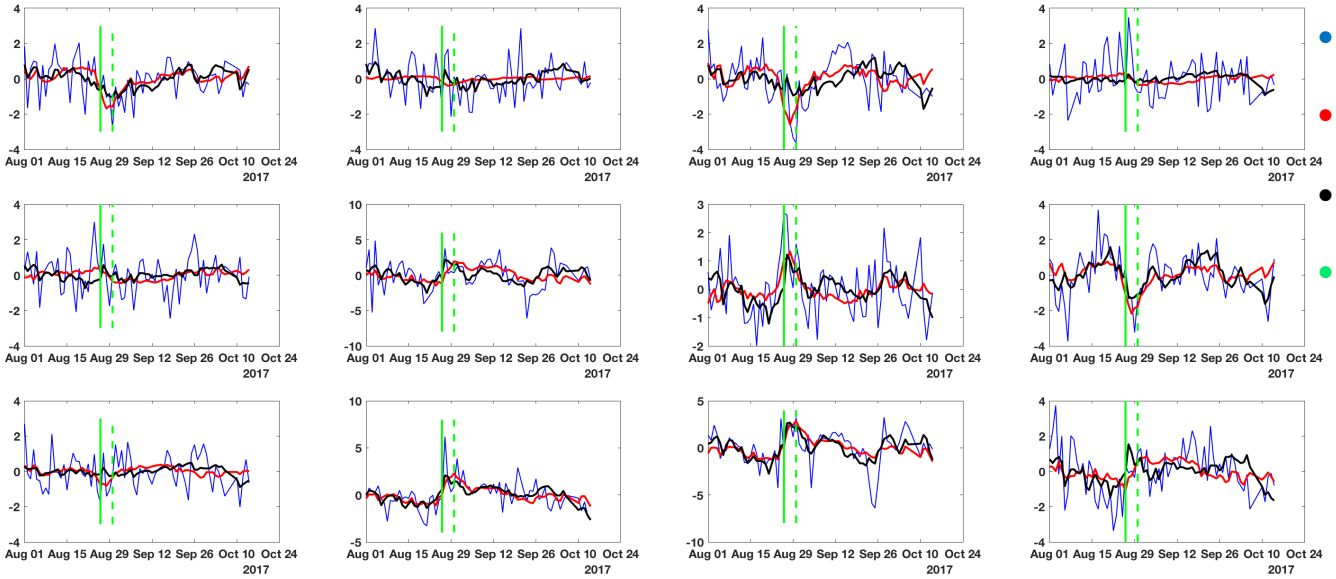


- PCA and ICA give similar results.
- Marked subsidence coincident with Harvey
- Return to pre-Harvey positions after ~5 weeks

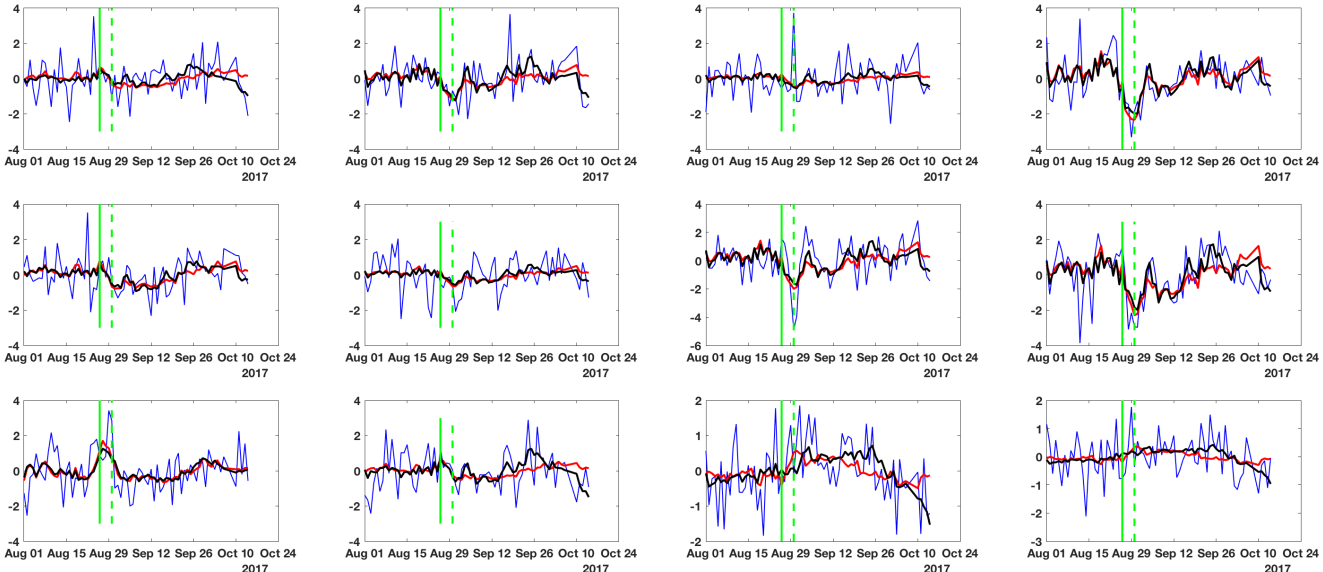
- **Blue = raw**
- **Red = ICA**
- **Black = PCA**
- **Green = Harvey landfall**

Data horizontals

North



East



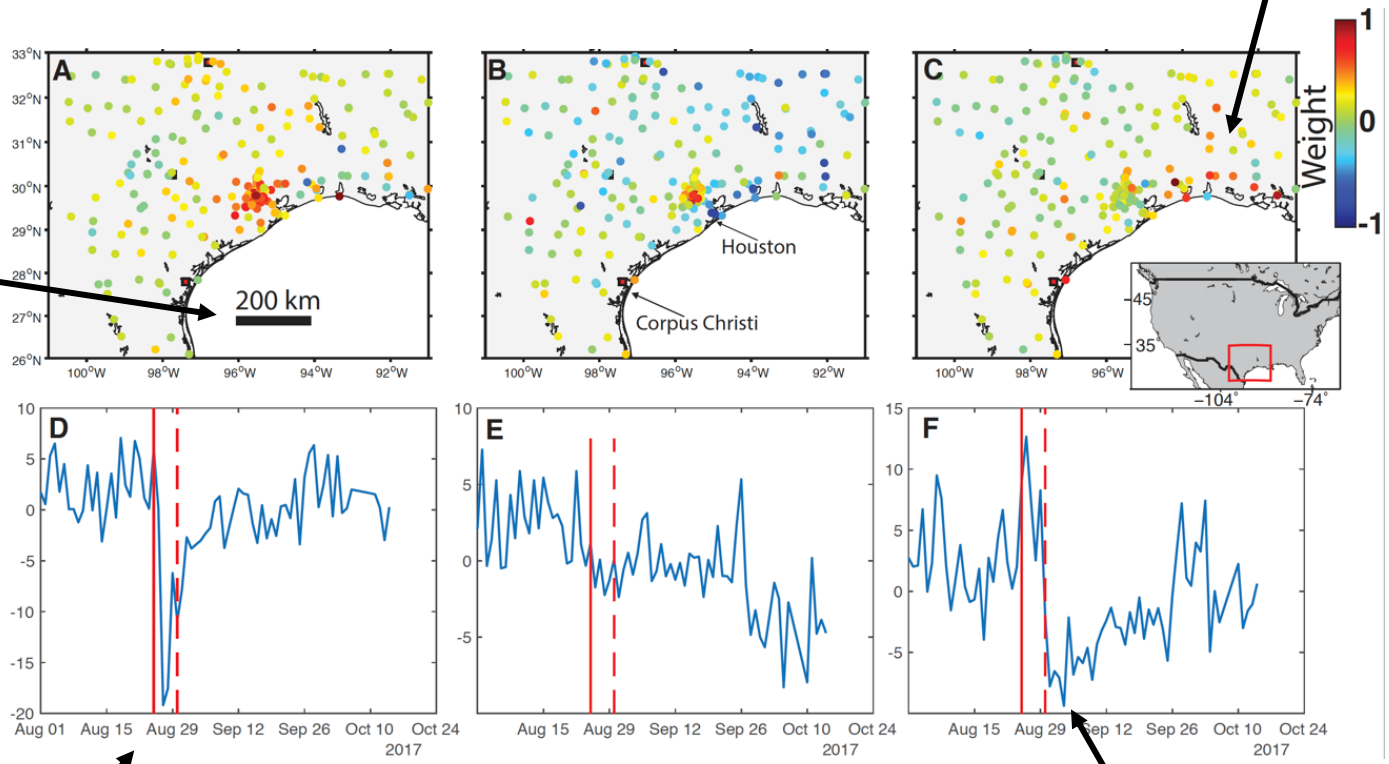
- **Blue = raw**
- **Red = ICA**
- **Black = PCA**
- **Green = Harvey landfall**

- Up to 4 mm change in position
- Coincident with Harvey
- Return to pre-Harvey positions after ~5 weeks

ICA filter

Hydrologic signal:
Area of second landfall

Hydrologic signal:
Area of known precipitation

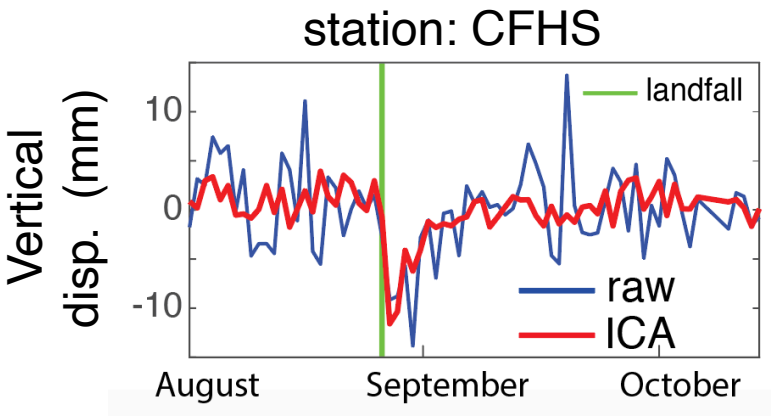


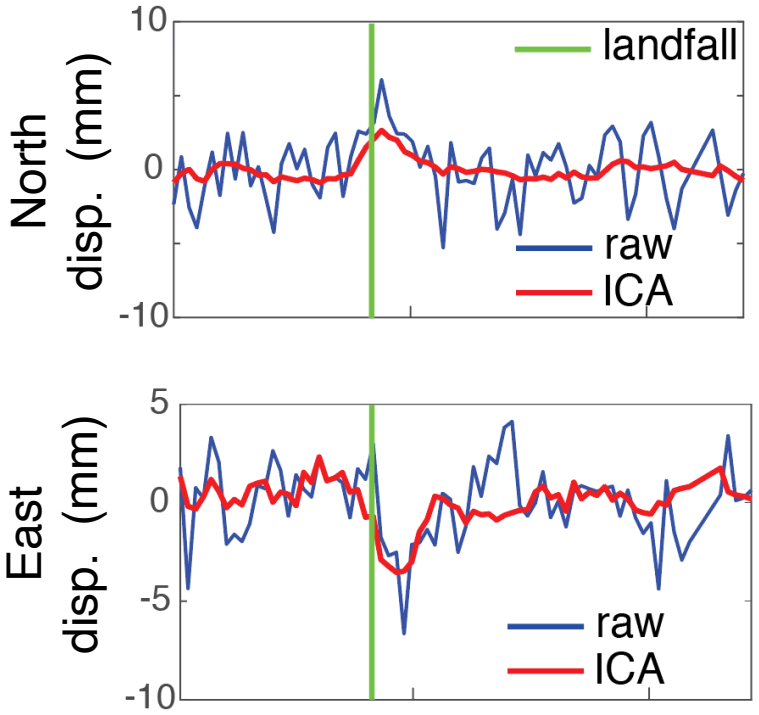
Hydrologic signal:
Coincident with initial landfall
Marked subsidence, gradual uplift

3rd component, a linear trend
Groundwater extraction

Hydrologic signal:
Coincident with second landfall
Marked subsidence, gradual uplift

Filtered timeseries



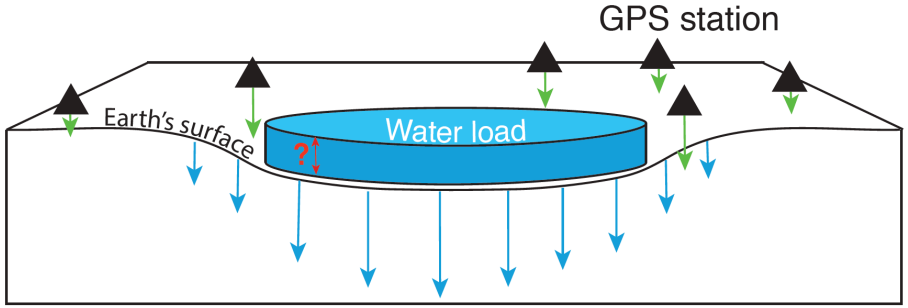


- RMS reduction of ~75%
- **Vertical**: Up to 21 mm vertical subsidence.
- **Horizontal**: Up to ~5 mm in horizontal direction.

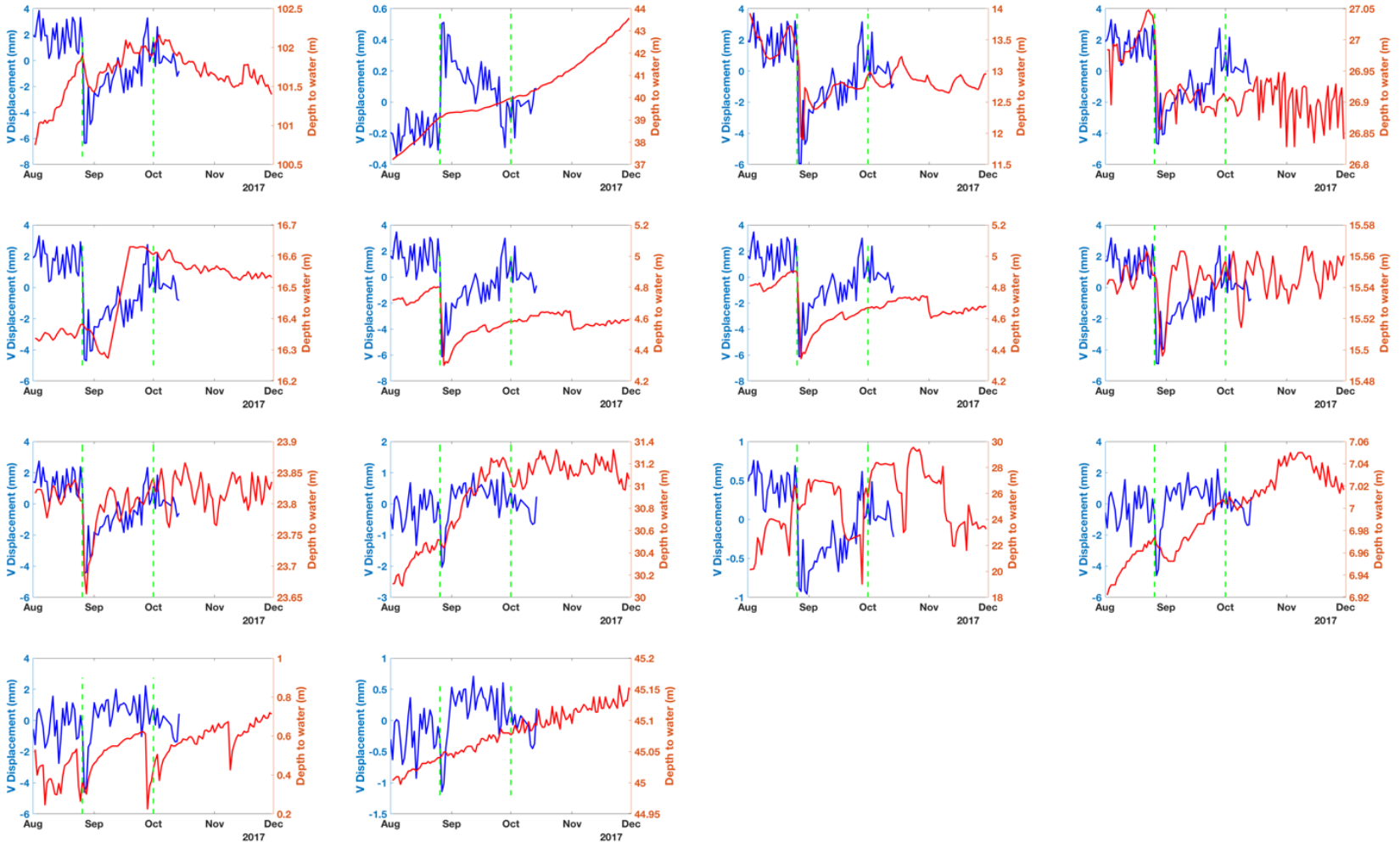
Invert GPS displacement → water mass

- Use all 3 components of motion
- Calculate water mass 25 km grid nodes.
- Green's functions relate GPS subsidence to water mass (Farrell, 1972; Adhikari et al., 2016).
  - Relates loading of a disk of unit thickness to surface motion.

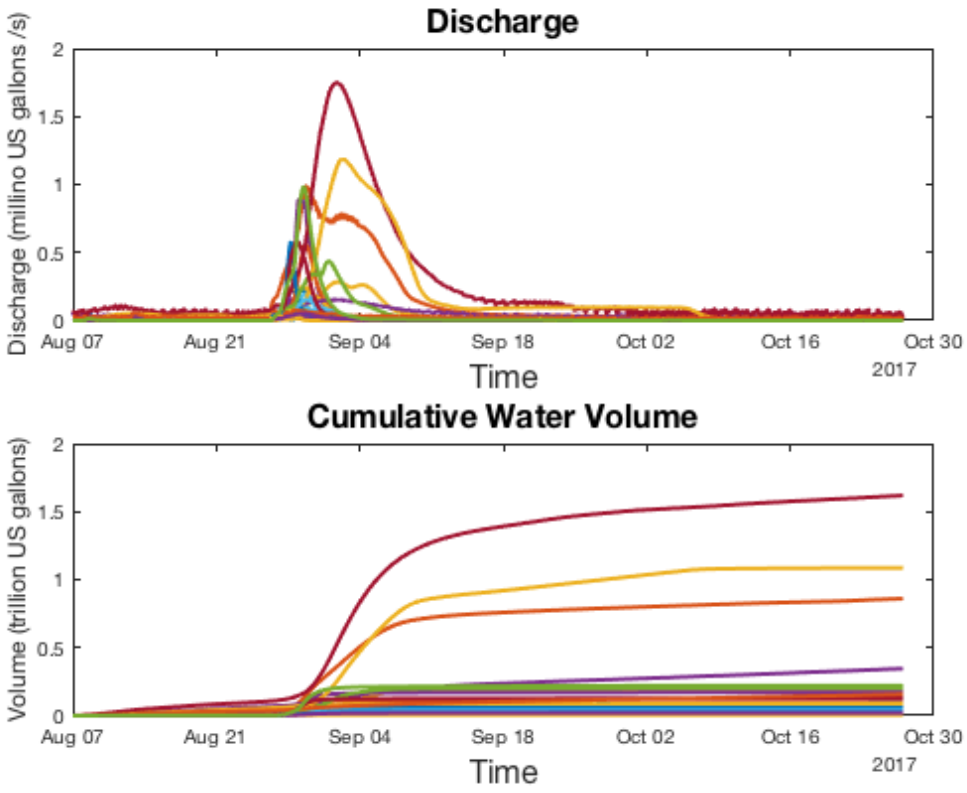
$$\begin{bmatrix} WG_v \\ WG_u \\ WG_u \\ \lambda S \\ \beta U \end{bmatrix} [m_t] = \begin{bmatrix} Wd_t^v \\ Wd_t^e \\ Wd_t^n \\ 0 \\ \beta U m_{t-1} \end{bmatrix}$$

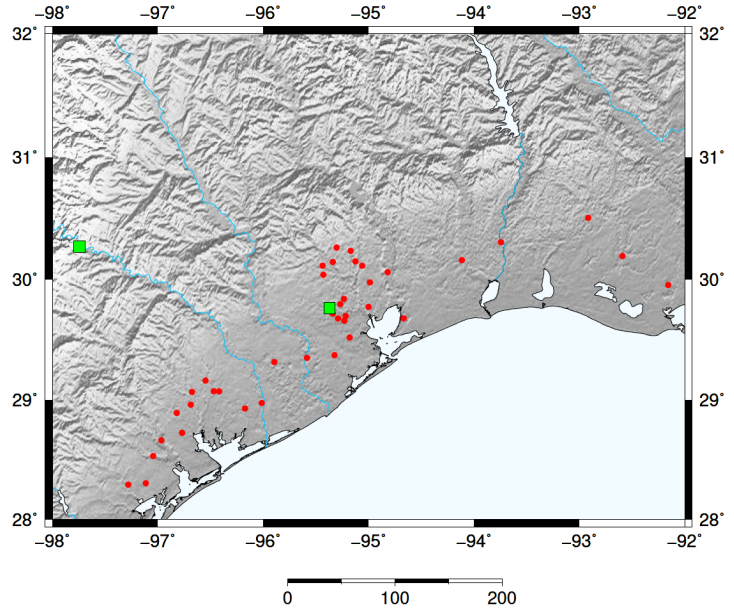


Poroelastic effects?

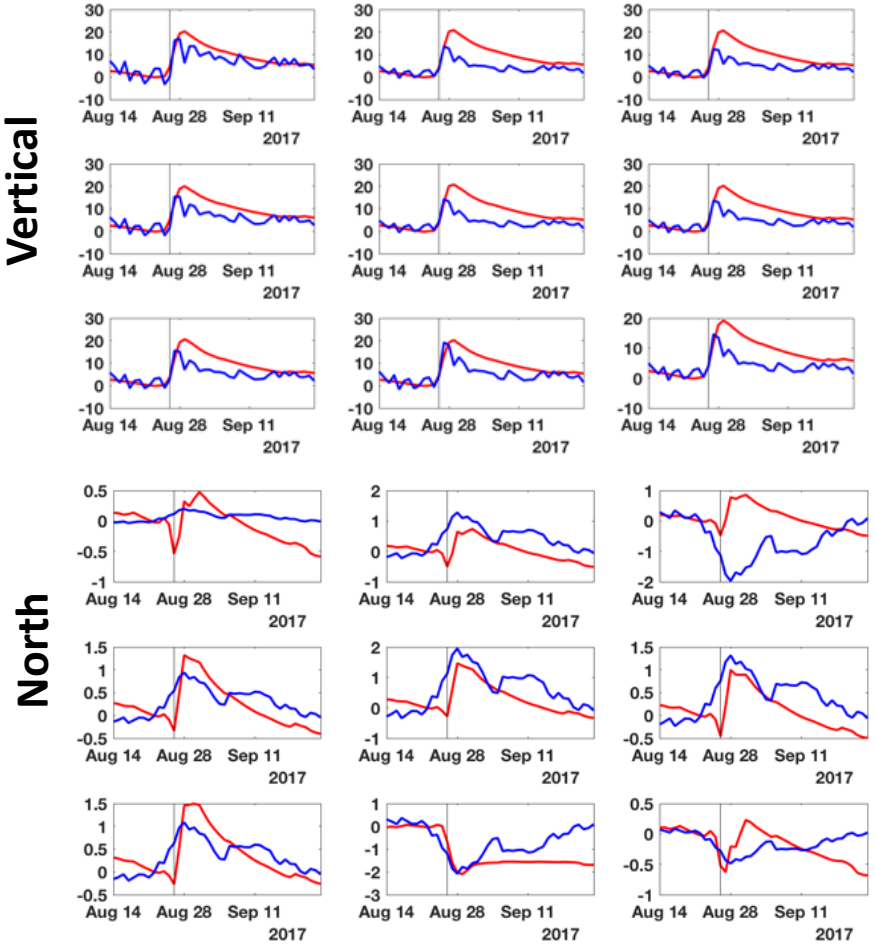


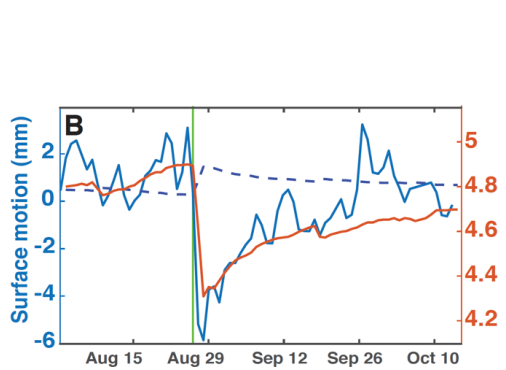
River discharge

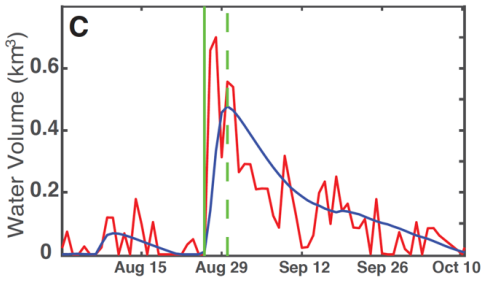




Validation





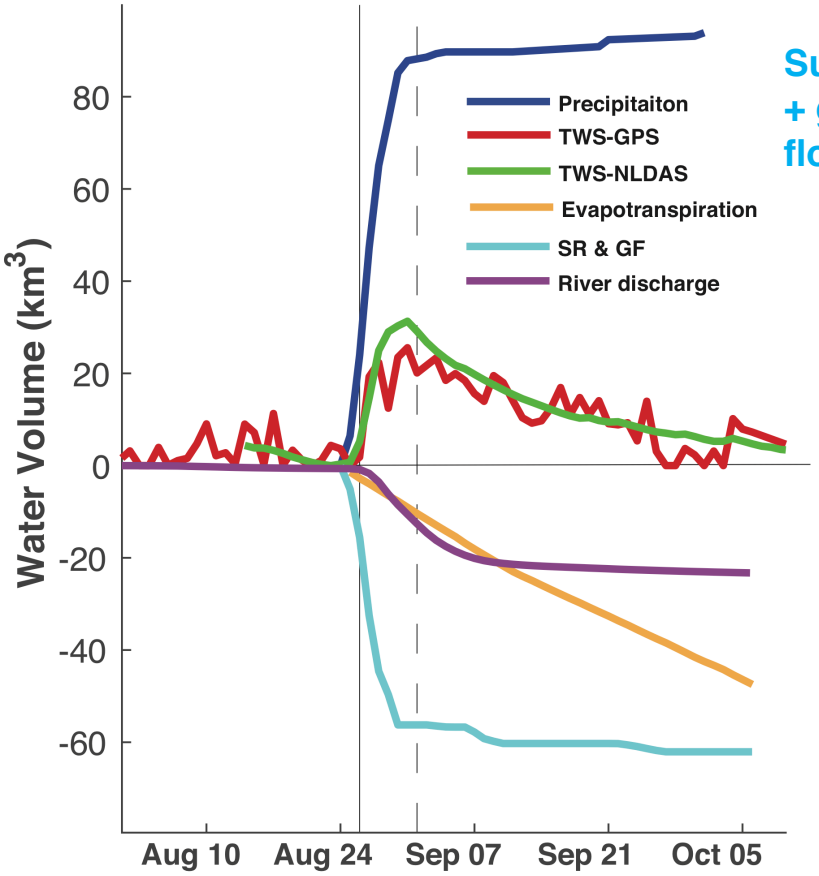


- NLDAS – National Land Data Assimilation model – hydrologic model driven by:
  - observed precipitation.
  - Shortwave radiation.
- Simulates TWS hourly and at 1/8^{o} degree

Well head water levels are inconsistent with poroelastic motions

USGS water volume measured at Barker and Addicks Reservoirs vs our TWS estimate

Hydrologic response



Water budget equation

$$S_t = P_t - \Delta TWS_t - ET_t$$

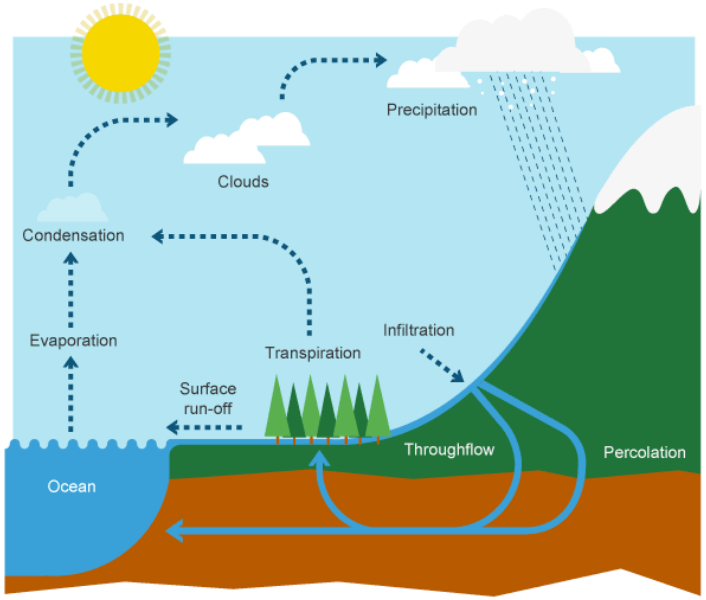
Surface runoff + groundwater flow

Precipitation

Water storage

Evapotranspiration

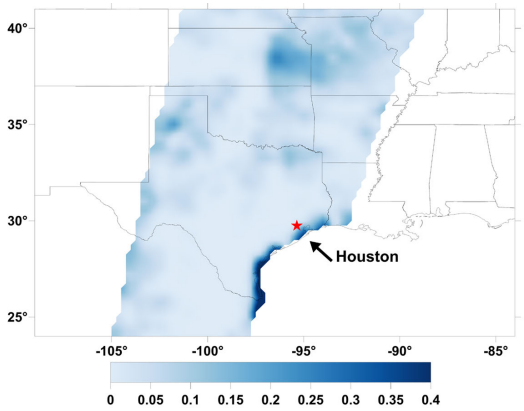
Fisher et al. (2008)



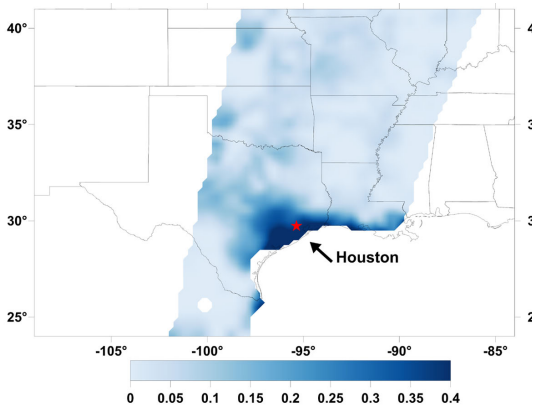
https://sciencestruck.com/water-cycle

- Knowing amount stored, can estimate amount 'not stored' → direct runoff + groundwater
- Indicates 60% of Harvey's stormwater was lost as initial pulse within first 7 days, at ~9 km^3/day.
- Surface runoff + groundwater flow (cyan) is ~3x that measured in river gauges (purple).

Validation

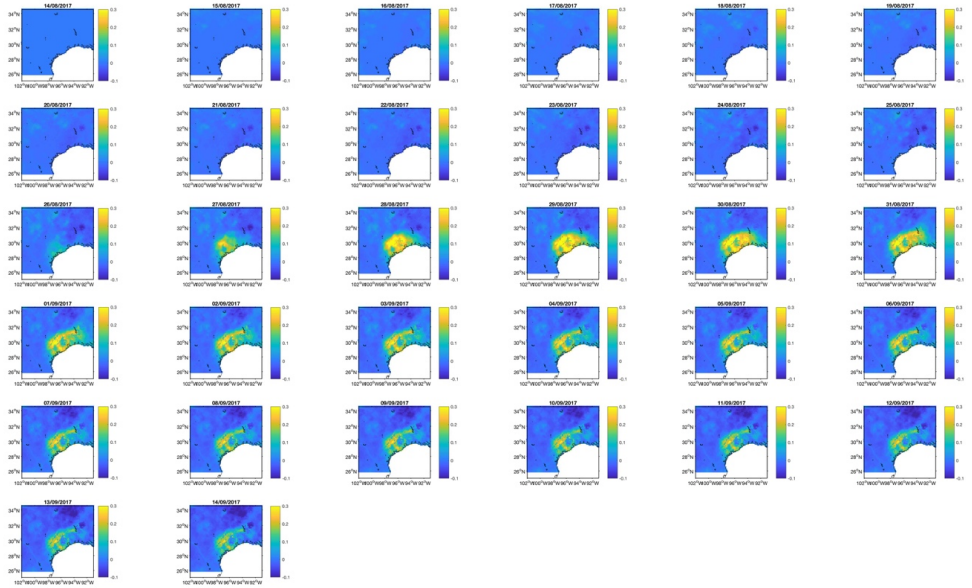


SMAP fractional open water for Aug. 22, 2017

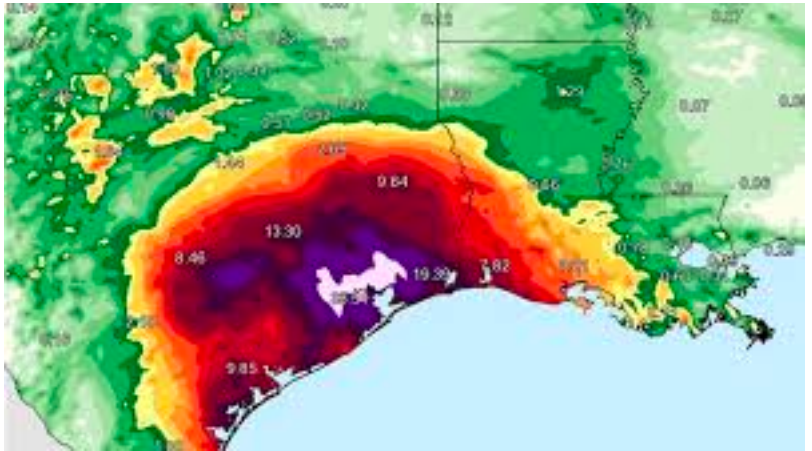


SMAP fractional open water for Aug. 27, 2017

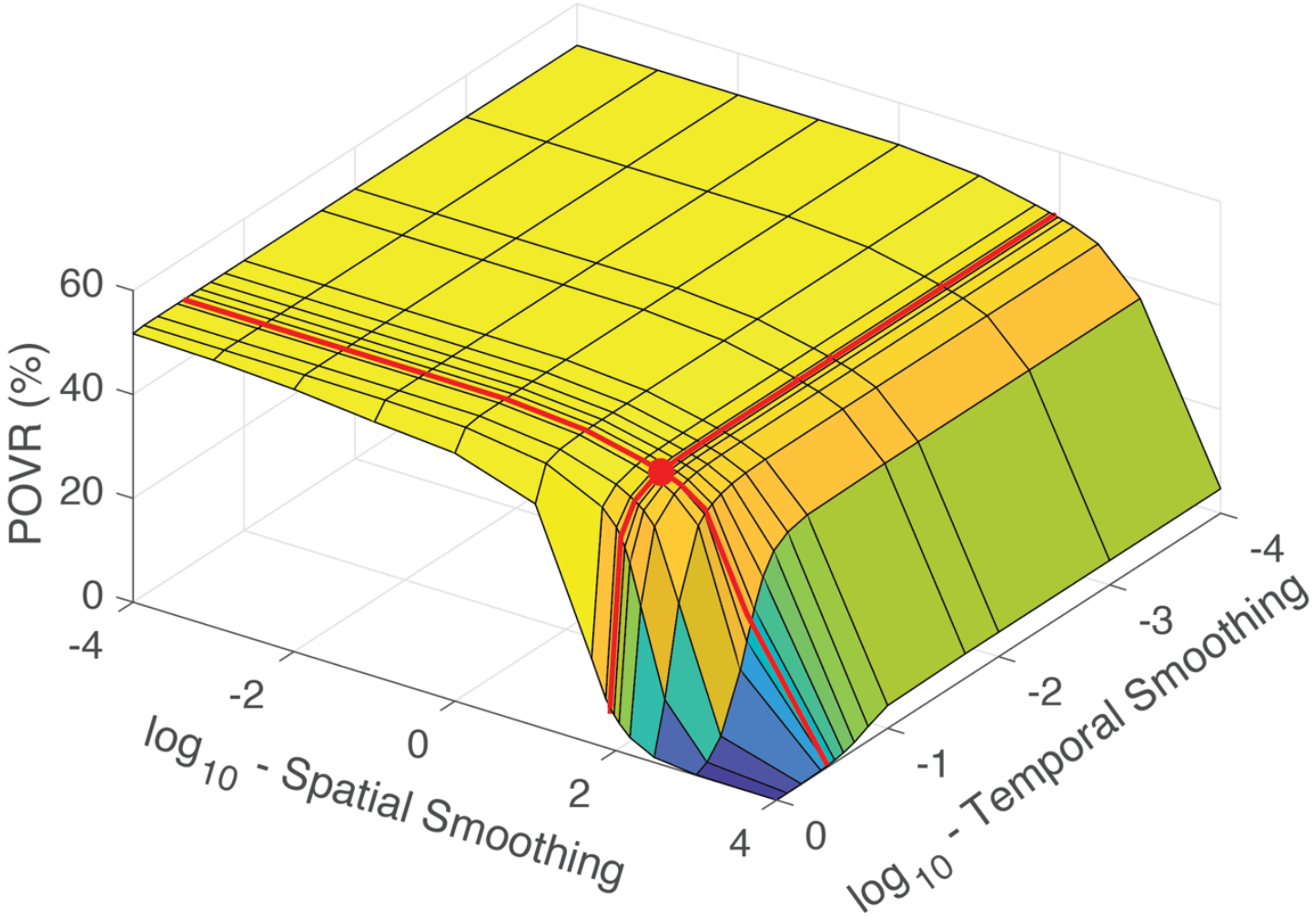
Images show the SMAP observations which detects the proportion of the ground covered by surface water within the satellite's field of view.



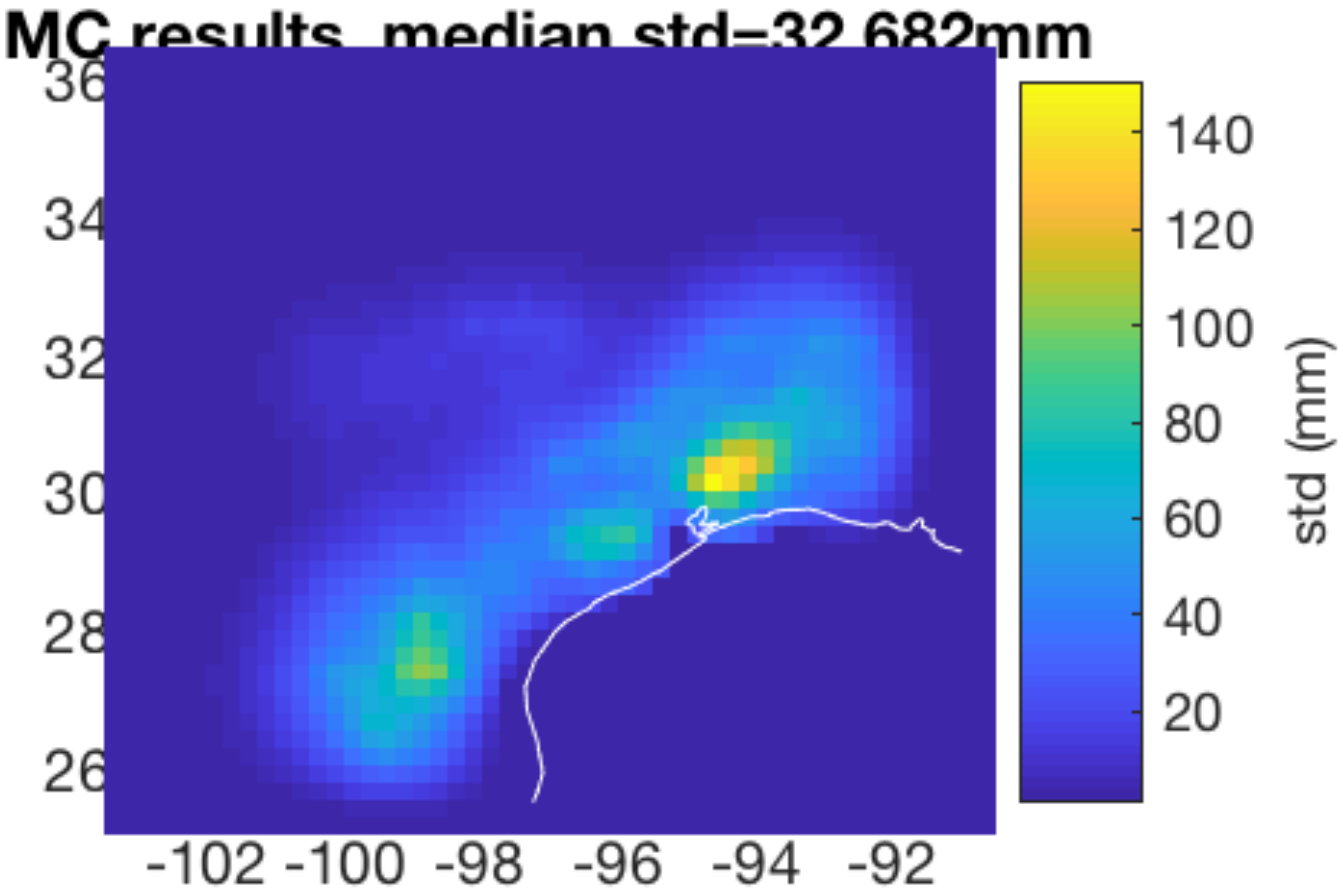
NLDAS – data assimilation hydrologic model.



Smoothing contraints - POVR



Model uncertainty



Conclusions

1. **ICA filter** can remove systematic bias helping resolve daily changes in water loading.
2. **GPS shows** up to 20 mm of subsidence, migrating land subsidence, followed by gradual uplfit
3. **Inverting** GPS → daily water mass:
    1. flooding extent
    2. rate of recovery storage capacity of system
4. TWS from GPS gives insight into:
    1. **how hydrologic system** responds to large influxes of water
    2. Existing missions measuring water storage.